THE QUIESCENCE OF DWARF NOVAE AND X-RAY TRANSIENTS

Kristen Menou

Chandra Fellow, Princeton University, Department of Astrophysical Sciences, Princeton, NJ 08540, USA

Abstract. Our understanding of the structure and properties of accretion disks in quiescent Dwarf Novae and X-ray Transients is very limited. Observations during quiescence challenge some of the standard Disk Instability Model (DIM) predictions. Our ignorance of the nature of viscosity may be the main source of uncertainties in quiescent disk models. A "layered accretion" alternative to the DIM, in which accretion proceeds via X-ray ionized surface layers, illustrates the magnitude of these uncertainties. A detection of molecular hydrogen in quiescent disks may provide direct constraints on the nature of viscosity.

1.   Introduction

Dwarf Novae (DN) and Soft X-ray Transients (SXTs) spend most of their lifetime in quiescence. According to the Disk Instability Model (DIM), mass builds up in an unsteady, neutral disk during this phase, until an outburst is triggered (Hameury, this volume; Lasota 2001).

While observations support our theoretical understanding of disk accretion during outburst, the quiescence phase is only poorly understood. In outburst, the presence of a hot, quasi-steady disk expected in the DIM picture is supported by eclipse mapping studies in DN (see, e.g., Horne 1993 for a review) and X-ray spectral fits in SXTs (e.g. Tanaka & Shibazaki 1996). There is every reason to believe that angular momentum transport in these disks is due to MHD turbulence resulting from the Magneto-Rotational Instability (MRI; Balbus & Hawley 1991, 1998; Balbus, this volume).

Observations in quiescence, however, are mostly puzzling, if not challenging the predictions of the DIM (see §2). The nature of viscosity in the neutral, quiescent disks is also uncertain, if not unknown (see §4). In these conditions, it is worth questioning the relevance of the DIM for describing the quiescence of DN and SXTs.

A brief summary of observational data on quiescent disks is first given in §2. A critical discussion of the reliability of various features in the DIM then follows in §3. The main factor limiting our understanding of quiescence in DN and SXTs may be our ignorance of the nature of viscosity in quiescent disks, as is discussed in §4. To illustrate this point, an alternative to the standard DIM picture is proposed in §5 in the form of a layered accretion toy model. The advantages and possible difficulties of this model are discussed in §6 before concluding in §7.

2.   Observations During Quiescence

2.1.   High Energy

Soft X-ray Transients (SXTs) –   Lasota (1996) pointed out that if quiescent disks in SXTs were accurately described by the DIM, accretion onto the compact object should proceed at a rate $\ll 10^{10}$ g s^{-1}, i.e. many orders of magnitude smaller than inferred from X-ray observations. In addition, at such a low rate, a thin accretion disk is not expected to emit a substantial amount of X-rays. This has led to the general belief that there cannot be a disk extending all the way down to the compact object in quiescent SXTs as would be expected in the DIM (see, e.g., Esin, McClintock & Narayan 1997). Wheeler (1996) also pointed out that the optical light from quiescent black hole SXTs (excluding the contribution from the companion star) corresponds to black body temperatures in excess of 10^4 K (see, e.g., Esin et al. 1997), which is too hot for the neutral disk expected in the DIM. It appears possible, however, that the quiescent optical luminosity of SXTs is powered by bright spot emission (Menou & McClintock 2001).

Nonetheless, the notion that a disk (evidenced by broad, double-peaked emission lines; e.g. Orosz et al. 1994) accumulates mass during quiescence to later power luminous outbursts seems quite reasonable.

Dwarf Novae (DN) –   Brown, Bildsten & Rutledge (1998) and Bildsten & Rutledge (2000; but see Lasota 2000) have proposed alternatives to accretion for powering the quiescent X-ray luminosity of SXTs. In quiescent DN, however, the shapes of X-ray eclipses in several quiescent DN shows that hard X-ray emission originates from the vicinity of the white dwarf (WD; Wheatley, this volume), making any alternative to boundary layer emission (and therefore accretion) rather implausible.

A significant increase of the accretion rate onto the compact object over the quiescence period is predicted by the DIM. This prediction is challenged by observations which show instead a (slightly) decreasing hard X-ray luminosity (van der Woerd & Heise 1987; Verbunt, Wheatley & Mattei 1999).

The decreasing UV fluxes observed in several quiescent DN could also be interpreted as challenging the DIM, but given that in some cases the UV light is clearly dominated by WD or accretion belt cooling (see, e.g., Sion 1999 for a review), this interpretation is subject to caution.

2.2.   Optical

One also expects the optical luminosity of the disk to increase during quiescence in the DIM. van Amerongen, Kuulkers & van Paradijs (1990), for instance, isolated the disk contribution in the quiescent lightcurve of Z Cha. They found that the disk contribution is nearly constant over the quiescence period, in contradiction with DIM predictions.

Eclipse mapping studies have revealed that quiescent disks in DN have brightness temperature profiles rising inward from ~ 5000 K to ~ 8000 K, with slopes significantly shallower than $R^{-3/4}$ (the expected scaling for the effective temperature of a steady-state disk, as observed in outburst; see, e.g., Horne 1993).

The colors and strong emission lines of quiescent disks in DN have long suggested emission from optically-thin gas (see, e.g., Robinson, Marsh & Smak 1993 for a review). Modeling this emission as an isothermal slab has systematically resulted in inferred values of the viscosity parameter α of several hundreds, much in excess of a reasonable $\alpha < 1$. It is therefore unclear whether these models, which require unsteady disks to reproduce the observed brightness temperature profiles, really support the DIM.

In addition, this type of models marginally reproduces the strength of the observed H emission lines, but is unable to account for the strong He lines observed (Robinson et al. 1993). Including high-energy irradiation in radiative models of quiescent DN disks seems required to reproduce these He lines (e.g. Patterson & Raymond 1985; Ko et al. 1996) and could result in large structural changes (e.g. vertical temperature inversion) with consequences for the emission that remain largely unexplored to date (Robinson et al. 1993).

3. Consequences for the DIM

The entirely optically-thin quiescent disk described by the isothermal slab model appears inconsistent with the DIM. Indeed, while the DIM would predict a typical surface density $\Sigma \sim 100$ g cm^{-2} at a radius of $\sim 10^{10}$ cm in a quiescent disk (e.g. Hameury et al. 1998), the isothermal slab model requires much smaller values of Σ for the slab to be optically-thin, typically < 1 g cm^{-2}.

The best attempt to date to compare observations of quiescent disks with expectations from the DIM is that of Idan et al. (1999). These authors calculated the emission from an unsteady quiescent disk (with an accretion rate $\dot{M}$ roughly $\propto R^3$, as predicted in the DIM) with Shaviv–Wehrse models (which include a treatment of the optically thin regions of the disk). By calibrating their models to the observed colors and inferred accretion rate of the DN HT Cas during quiescence, they concluded that a viscosity parameter $\alpha > 1$ is required to fit the observations. Idan et al. emphasize that this value is inconsistent with the typical value $\alpha_{\rm cold} \sim 0.01$ inferred from modeling DN recurrence times with the DIM.

To date, the most realistic radiative models of quiescent disks (as described by the DIM) are therefore not internally consistent. It is worth noting, however, that the models of Idan et al. also neglect the role of high-energy irradiation (required to reproduce the observed He lines). Although this may not solve the $\alpha > 1$ problem, there is in principle still room for improvement. Nonetheless, the discrepancies between the quiescent variations of the hard X-ray and optical luminosities expected in the DIM and the observations seriously challenge the model.

Because of this, it is worth considering which of the DIM features for quiescent disks are reliable. The idea that mass accumulates during quiescence to power the luminous disk outbursts is certainly supported by observations in a general sense. Another feature of the DIM that appears reliable is the initial quiescent profile of surface density Σ in the disk (immediately following the propagation of a cooling front), because it is independent of the adopted value of $\alpha_{\rm cold}$ when $\alpha_{\rm cold} \ll \alpha_{\rm hot}$ (Menou, Hameury & Stehle 1999). The subsequent disk evolution and most of the other quiescent disk features in the DIM are ques-

tionable, however, because of our ignorance of the nature of viscosity in these disks. In particular, the global stability criterion on the mass accretion rate, $\dot{M}_{\rm crit}^{-}(R)$, used to determine when an outburst is triggered may not be reliable.

4. Nature of Viscosity

4.1. MHD Turbulence

The MRI most likely operates in hot disks during outbursts, leading to efficient MHD-turbulent transport. The situation for quiescent disks is much less clear, however. Non-ideal MHD effects become important in a weakly-ionized gas. Resistive diffusion should be the dominant such process in quiescent disks (Gammie & Menou 1998). Hall effects contribute to a smaller extent, given the typical densities $n \sim 10^{18}$ cm^{-3} expected (and making the reasonable assumption that gas pressure dominates over magnetic pressure; Balbus & Terquem 2001).

To date, various estimates and numerical simulations have suggested that MHD turbulence dies away in quiescent disks (Gammie & Menou 1998; Fleming, Stone & Hawley 2000; Menou 2000). These works have neglected Hall effects, however. Future work including Hall effects will verify if MHD turbulence indeed shuts off in quiescence or if a residual, low-level of MHD turbulence is expected (Balbus, this volume).

4.2. The Role of Molecular Hydrogen

It is worth emphasizing here that the suppression of MHD turbulence in quiescent disks seems to require hydrogen to be in molecular phase, simply because dissociative recombination is several orders of magnitude more efficient than atomic hydrogen recombination (see §5.1). In that sense, a direct detection of molecular hydrogen would likely provide strong constraints on the nature of viscosity in quiescent disks. Band diagnostics may reveal the gas temperature and density in the disk, which would allow a direct, *in situ* measure of the strength of non-ideal MHD effects.

4.3. Other "Viscosity" Mechanisms?

Numerical simulations of Keplerian disks, which show the development of turbulence and efficient transport in the magnetized case but not in the unmagnetized case, support the idea that disks are hydrodynamically stable (Hawley, Balbus & Winters 1999; see Richard & Zahn 1999 for a different view). In addition, while spiral density waves may play a role in determining outburst recurrence times (Menou 2000), they are not expected to be present in quiescent disks because of the inefficient coupling of the companion tidal field with a cold disk (Boffin, this volume). Finally, disk self-gravitation is probably irrelevant for quiescent disks in DN and SXTs given the relatively small disk masses involved and the disk floor temperature expected, e.g., from irradiation by the companion star. In other words, if MHD turbulence dies away in (the bulk of) a quiescent disk, there may be no other mechanism for transporting angular momentum. This is the main motivation for studying layered accretion. (Of course, layered accretion could still be relevant even if there is a residual viscosity in the bulk of quiescent disks).

5. Layered Accretion Toy Model

The layered accretion model presented here is inspired by Gammie's (1996) proposal for T-Tauri disks. In Gammie's picture, cosmic-rays penetrate a layer ~ 100 g cm^{-2} deep and provide non-thermal ionization allowing MHD turbulence to develop and accretion to proceed in disk surface layers. In between the two active layers lies a dead zone, where no accretion occurs if no viscosity mechanism operates.

One easily shows that, in DN (and SXT) quiescent disks, cosmic ray ionization is rather inefficient because of the much larger densities involved. On the other hand, hard X-ray emission, typically at a level of 10^{31} erg s^{-1} (and Bremsstrahlung temperatures $kT \sim 1-10$ keV) may provide the required ionization level for MHD turbulence to develop in surface layers. (Irradiation also constitutes an extra source of heating for the disk, but it is generally negligible when compared to viscous dissipation in the active layers).

The cross-section of a $5-7$ keV X-ray photon in a solar-composition material approximately corresponds to ~ 1 g cm^{-2}, so that this value is chosen for the normalization of the active layer surface density, Σ_a (ignoring geometrical effects). Softer X-ray photons have a larger cross-section and therefore penetrate less deep inside the disk (and vice-versa; Morrison & McCammon 1983). Note that a layer of ~ 1 g cm^{-2} with a temperature of a few 1000 K (see solution below) should be optically-thin.

5.1. Equations

Mass and angular momentum conservation in the steady-state, active layers yields

$$\dot{M} = 6\pi R^{1/2} \frac{\partial}{\partial R}\left(2\Sigma_a \nu R^{1/2}\right), \tag{1}$$

where $\dot{M}$ is the summed accretion rate in the 2 active layers, ν is the kinematic viscosity in these layers and R is the distance from the central object. Conservation of the viscously-dissipated energy yields

$$\frac{9}{4}\nu\Sigma_a\Omega_k^2 = \sigma T_{\rm eff}^4, \tag{2}$$

where Ω_k is the Keplerian angular rotation speed and $T_{\rm eff}$ is the effective temperature of the active layers. The radiative transfer (assumed optically-thin) is accounted for in the simplest way:

$$\tau T_c^4 = T_{\rm eff}^4, \ \ \tau = \Sigma_a\kappa_p, \tag{3}$$

where T_c is the temperature of the active layers, τ is the optical thickness of each active layer and κ_p a Planck-mean opacity. Finally, a standard Shakura–Sunyaev α–viscosity is assumed:

$$\nu = \alpha c_s^2/\Omega_k. \tag{4}$$

The above equations are closely related to the standard steady-state thin disk equations with the additional assumption of optically-thin radiative transfer.

The flux irradiating the disk is taken as

$$F_x \approx \frac{L_x}{4\pi R^2} \frac{H}{R},\tag{5}$$

where H is the disk geometrical thickness. The ratio H/R should reasonably approximate the irradiation geometry if the hard X-rays originates in a hot, optically-thin boundary layer of size comparable to the WD. The volumic ionization rate is therefore

$$\xi_i \approx \frac{L_x}{4\pi R^3 E_i} \frac{H}{H_a},\tag{6}$$

where H_a, the active layer thickness, has been introduced for generality and $E_i \approx$ 37 eV is the typical energy required for secondary electron generation (Glassgold, Najita & Igea 1997). The volumic recombination rate for a predominantly-atomic hydrogen gas is $\xi_r \approx 6.68 \times 10^{-13} n_e^2 (T_c/3000 \text{ K})^{-0.8} \text{ cm}^3 \text{ s}^{-1}$ (n_e is the electron number density); it becomes much faster for a predominantly-molecular hydrogen gas, with $\xi_r \approx 8.7 \times 10^{-6} n_e^2 T_c^{-0.5} \text{ cm}^3 \text{ s}^{-1}$ (dissociative recombination).

The magnetic Reynolds number in the active layers can be calculated according to

$$Re_M \equiv \frac{c_s H_a}{\eta}, \eta = \frac{c^2 m_e \nu_{en}}{4\pi n_e e^2},\tag{7}$$

where c_s is the sound speed in the active layers, η is the resistivity, proportional to the electron-neutral collision frequency, ν_{en}, and other symbols have their usual meaning (Gammie & Menou 1998). The equivalent dimensionless number measuring the strength of ambipolar diffusion is

$$Re_A = \frac{\nu_{ni}}{\Omega_k},\tag{8}$$

proportional to the ion-neutral collision frequency, ν_{ni} (Menou & Quataert 2001).

5.2.   Solution

The above structural equations are solved assuming, instead of a constant $\dot{M}$ with radius like in the Shakura-Sunyaev solutions, a constant surface density with radius, Σ_a (in g cm^{-2}), in the active layers.

Structure–   The temperature, effective temperature and accretion rate of the active layers scale as

$$T_c = 3357 \text{ K } \left(\frac{\kappa_p}{0.1}\right)^{-1/3} \alpha_{0.1}^{1/3} m_1^{1/6} R_{10}^{-1/2},\tag{9}$$

$$T_{\text{eff}} = 1888 \text{ K } \Sigma_a^{1/4} \left(\frac{\kappa_p}{0.1}\right)^{-1/12} \alpha_{0.1}^{1/3} m_1^{1/6} R_{10}^{-1/2},\tag{10}$$

$$\dot{M} = 1.4 \times 10^{14} \text{ g s}^{-1} \Sigma_a \left(\frac{\kappa_p}{0.1}\right)^{-1/3} \alpha_{0.1}^{4/3} m_1^{-1/3} R_{10},\tag{11}$$

where an arbitrary $\kappa_p = 0.1$ and $\alpha_{0.1} = \alpha/0.1 = 1$ have been assumed, m_1 is the central object mass in solar units and R_{10} is the distance from the accretor

in units of 10^{10} cm. A typical mass density in the active layers is $\rho = \Sigma_a/H_a \sim 10^{-8}$ g cm^{-3}. Assuming that no viscous dissipation occurs in the dead zone, it should be isothermal with $T \sim T_c$, if conduction between active and dead layers is efficient (i.e. at thermal equilibrium). In the limit where conduction is inefficient, the dead zone (assumed optically-thick) should have $T \sim T_{\rm eff}$ since it absorbs and reradiates about half the flux emitted by the optically-thin active layers.

To within an order of magnitude or so, the above accretion rate, at $R \simeq 10^9$ cm (an appropriate disk inner radius in the case of accretion onto a WD), is sufficient to power 10^{31} erg s^{-1} in a quiescent DN. Note that $\dot{M}$ does not depend on L_x, which guarantees stability against fluctuations of L_x as often observed in quiescent DN. (L_x determines the quality of gas-field coupling in the active layers, however, via Eq. [6]). The scaling of $\dot{M}$ with Σ_a implies instead a sensitivity to the spectrum of irradiating photons.

Ionization Properties – The values of the electron density, ionization fraction, magnetic Reynolds number and equivalent for ambipolar diffusion, in the active layers, scale as

$$n_e = 1.4 \times 10^{11} \text{ cm}^{-3} \left(\frac{T_c}{3000 \text{ K}}\right)^{0.4} \left(\frac{L_x}{10^{31} \text{ erg s}^{-1}}\right)^{1/2} \left(\frac{H_a}{H}\right)^{-1/2} R_{10}^{-3/2}, \quad (12)$$

$$x_i = 10^{-5} \ \Sigma_a^{-1} m_1^{-1/2} \left(\frac{T_c}{3000 \text{ K}}\right)^{0.9} \left(\frac{L_x}{10^{31} \text{ erg s}^{-1}}\right)^{1/2} \left(\frac{H_a}{H}\right)^{1/2}, \quad (13)$$

$$Re_M = 1.5 \times 10^4 \ \Sigma_a^{-1} m_1^{-1} \left(\frac{T_c}{3000 \text{ K}}\right)^{1.4} \left(\frac{L_x}{10^{31} \text{ erg s}^{-1}}\right)^{1/2} \left(\frac{H_a}{H}\right)^{1/2} R_{10}^{3/2}, \quad (14)$$

$$Re_A = 700 \ m_1^{-1/2} \left(\frac{T_c}{3000 \text{ K}}\right)^{0.4} \left(\frac{L_x}{10^{31} \text{ erg s}^{-1}}\right)^{1/2} \left(\frac{H_a}{H}\right)^{-1/2}, \quad (15)$$

where a fixed temperature value, $T_c = 3000$ K, has been used in these estimates for simplicity. A comparison of Re_M and Re_A above to existing estimates of the critical values ($Re_{M,c} \sim 10^4$, $Re_{A,c} \sim 100$; Fleming et al. 2000; Hawley & Stone 1998) below which MHD turbulence cannot be self-sustained suggests only marginal gas-field coupling in the active layers.

Note that at $T_c \sim 3000$ K, the dead zone ($\rho \sim 10^{-6}$ g cm^{-3}) is predominantly molecular, while the active layers ($\rho \sim 10^{-8}$ g cm^{-3}) are predominantly atomic (see, e.g., Lenzuni, Chernoff & Salpeter 1991). This justifies the use of the slower recombination rate ξ_r for an atomic gas in the solution above. If hydrogen were predominantly molecular in the active layers, the value of Re_M would be several orders of magnitude smaller than indicated above.

5.3. Mass Accumulation

Growth Timescale – The accretion rate in the active layers, $\dot{M}$, decreases with radius, so that mass accumulates in the dead zone as a function of time, according to

$$\frac{\partial \Sigma_d}{\partial t} \equiv \frac{1}{2\pi R} \frac{\partial \dot{M}}{\partial R}. \quad (16)$$

Approximating the initial quiescent density profile in the dead zone as $\Sigma_d \sim \Sigma_{\min}$ ($\alpha = 0.1$) $\propto R_{10}^{1.11}$ (e.g. Hameury et al. 1998), the timescale over which mass build ups in the dead zone is then

$$\frac{\Sigma_d}{\partial \Sigma_d / \partial t} = 7.2 \text{ yrs } \Sigma_a^{-1} m_1^{-0.04} \alpha_{0.1}^{-2.1} \left(\frac{\kappa_p}{0.1} \right)^{1/3} R_{10}^{2.11}, \qquad (17)$$

which corresponds to the interesting values of ~ 20 days at $\sim 10^9$ cm (disk inner radius in the DN case) and ~ 30 years at $\sim 2 \times 10^{10}$ cm (a typical disk transition radius in the quiescent BH SXT models of Esin et al. 1997). These timescales are comparable to the typical recurrence times of DN and BH SXTs, respectively. Mass could also accumulate in the disk outer regions for which Eq. (11) indicates accretion rates smaller than typical mass transfer rates (at least in some systems). Note also that $\Sigma_{\min}$ becomes < 1 g cm^{-2} (the typical penetration scale of photoionizing X-ray photons) at radii smaller than $\sim 3 \times 10^8$ cm. Consequently, a fully active, steady-state disk (i.e. without a dead zone or mass accumulation) is expected at small radii (at least in SXTs).

How to Trigger Outbursts? – Mass accumulation by itself does not result in outbursts. If there is a residual viscosity in the "dead" zone, however, the viscous torque and viscous dissipation, both $\propto \Sigma_d$, will build up with time ($\alpha_{\rm dead}$ could be $<< 1$). In these conditions, the central temperature in the likely optically-thick, "dead" zone will also increase with time, potentially resulting in sufficient thermal ionization at late times to initiate MHD turbulence and a global disk outburst. An interesting candidate for the residual viscosity process is a Reynolds (i.e. hydrodynamical) stress induced in the "dead" zone by the MHD turbulence in the active layers, as found by Fleming & Stone (2001) in their numerical simulations of layered accretion for T-Tauri disks.

6.   Discussion

As a model of quiescent accretion in DN (and possibly SXTs), the layered accretion toy model outlined above has several advantages and shortcomings. With $\Sigma_a \sim 1$ g cm^{-2} and $T_c \sim$ a few 10^3 K, optically-thin gas emission is expected from the active layers. The profile of effective temperature ($T_{\rm eff}(R) \propto R^{-1/2}$) is flatter than for a steady-state disk ($R^{-3/4}$) and probably in reasonable agreement with inferences from quiescent eclipse maps. Angular momentum transport is solely provided by the well understood MRI (MHD turbulence) in this scenario. Contrary to the DIM, no increase in $\dot{M}$ during quiescence is expected in this scenario (though no decrease is expected either). The important high-energy irradiation of quiescent disks is a crucial component of the model which is often ignored in other descriptions of quiescent disks. Finally, various scalings in the layered accretion solution are, at an order of magnitude level, in agreement with observationally inferred values, such as the quiescent accretion rate onto WDs in DN. One certainly cannot ask much more from such an idealized, toy model.

The extremely crude optically-thin radiative transfer treatment or the 1–zone approximation are examples of obvious oversimplifications in the model. The only marginal MHD coupling of the active layers can also be considered

as a weak point of the model (though Hall effects may help gas-field coupling in this low-density case). Fine-tuning may be required to guarantee, e.g., the predominantly-atomic nature of the active layers on top of a predominantly-molecular dead zone. It is also unclear how well the model applies to SXTs since, for instance, disk self-irradiation could be much less in BH SXTs than irradiation by the central WD in DN (though reprocessing by a hot extended medium such as an ADAF may help). Finally, because the simulations of Fleming & Stone show that the magnitude of induced-viscosity in the dead zone decreases for larger ratios of dead-zone to active-layer mass, an additional, yet unidentified viscosity mechanisms may be required, in the end, to trigger outbursts in the dead zone.

Nonetheless, the layered accretion toy model has the important advantage of offering a plausible alternative to the quiescent disk structure predicted by the DIM and challenged by observations of quiescent DN. At the very least, the layered accretion scenario should be used as a measure of our poor understanding of quiescent disks due to our ignorance of the nature of viscosity in these disks. In that respect, it is quite significant that the typical value of $\alpha_{\rm cold} \sim 0.01$ inferred from DN recurrence times does not necessarily measure an actual efficiency of angular momentum transport in the layered accretion scenario but rather corresponds to the timescale for mass accumulation in the dead zone (α being presumably ~ 0.1 in well-coupled active layers and possibly $<< 0.01$ in the dead zone).

7. Conclusion

The unknown nature of viscosity in the quiescent disks of DN and SXTs results in considerable uncertainty on the structure and properties of these disks. Layered accretion appears as a plausible alternative to the standard DIM picture, although additional work is clearly required to validate this scenario.

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